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Profs. R. .T. Guza and Falk Feddersen

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Scripps Institutions of Oceanography
IOD/SIO/UCSD 0209
9500 Gilman Drive
La Jolla CA 92093-0209

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14. ABSTRACT
The RIVET I field experiment took place in a small inlet with strong tidal currents, and moderate waves that broke on a shallow ebb shoal. The fate of littoral tracers is of significant Naval interest, relevant to chemically detecting mines, avoiding dangerous substances, and predicting where optical. The project objective, to measure mixing and transport in a small tidal inlet, was achieved in the RIVET 1 experiment. During RIVET I, we measured transport and dispersion from within the New River Inlet to 2-3 km offshore and alongshore. The detailed are objectives 1) quantify the transport and mixing of tracer and 2) use this quantification to test numerical models.

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Transport and Dispersion of Dye-tracer and Drifters at a Tidal Inlet

Profs. R. .T. Guza and Falk Feddersen
Scripps Institutions of Oceanography
IOD/SIO/UCSD 0209, 9500 Gilman Drive, La Jolla CA 92093-0209
858.534.4345, 858.534.0300 (FAX)
rguza@ucsd.edu, falk@coast.ucsd.edu
http://iod.ucsd.edu/∼falk

Award Number: N00014-13-1-0126

LONG-TERM GOALS

Our *long-term goals* include developing and field-testing numerical models of shallow water breaking waves and wave-driven processes, including currents, and tracer transport and dispersion. Improved prediction of the fate of terrestrial runoff pollution and other substances (e.g. fine sediment, chemicals) sometimes present in very shallow water.

OBJECTIVES

The objective of this project, to measure mixing and transport in a small tidal inlet, was achieved in the RIVET 1 experiment. During RIVET I, we measured transport and dispersion from within the New River Inlet to 2-3 km offshore and alongshore, at different tidal stages. Analysis of this diverse data set of waves, currents, stratification, Lagrangian drifter, and dye-tracers in conjunction with analysis and comparison of numerical simulations is ongoing. The detailed objectives were to

- Quantify the transport and mixing (dilution or dispersion) of Lagrangian quantities (dye and tracer) within the inlet and the surrounding ocean.
- Use this quantification from observations to test numerical simulations.

APPROACH

RIVET-I observations were collected from May 1-21 with instrument deployment in late April and recovery in late May at the New River Inlet N.C. (Figure 1). The inlet had a fierce concentration of remote- and in situ observations - some of which are indicated in Figure 1. Many of these locations held a current meter, pressure sensor, and a fluorometer. During the observation period, summaries of recent observations and upcoming activities were regularly posted to `http://blogs.iod.ucsd.edu/RIVET`, a community blog that we created. Our diverse data set has been quality controlled and all data has been posted to the blog site above and is freely available to all other ONR RIVET investigators.

There approach used here is multi-pronged:

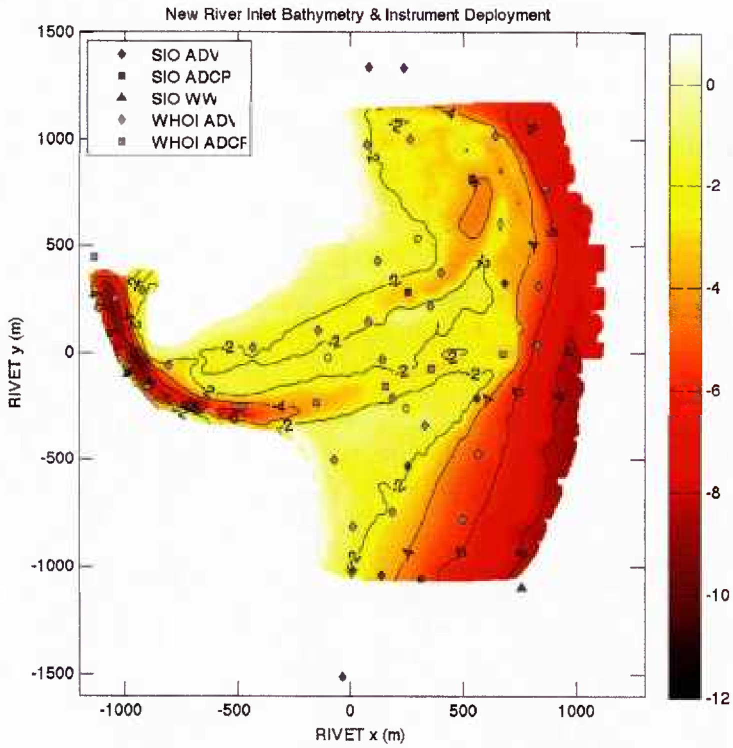

Figure 1: Map of New Rivet Inlet NC bathymetry (from the ASACE FRF) in the RIVET coordinate system with the SIO (Feddersen/Guza) and WHOI (Raubenheimer/Elgar) ADV, ADCP, and wirewalker (WW) instrument locations as noted in the legend. The TopSail side of the inlet is below and the Camp Lejuene side is on top. SIO ADV locations are marked V1-V8. All locations also had a co-located pressure sensor and many locations also had a co-located Rhodamine WT dye fluorometer. Dye was released either near $x \approx -600$ m and $y \approx -300$ m, or about 1.2 km further up the inlet towards the Inter-Coastal Waterway.

1. Develop and test an algorithm for converting aerial hyperspectral images of the ocean surface to calibrated dye concentration in parts per billion (ppb).
2. Quantify the dye transport and mixing dilution
3. Perform numerical simulations using the COAWST (coupled ROMS/SWAN) modeling system. Test the model with the array of current meters and pressure sensors deployed in the inlet.
4. Perform numerical dye release experiments and compare these to the observations.

Similar approaches are used for analysis and modeling of the New River Inlet drifter releases.

WORK COMPLETED This effort began in March of 2013. The following tasks have been completed.

- Quality control and public posting of all the data has occurred
- Method for quantitive aerial dye measurements has been developed [*Clark et al.*, 2014] and published in *J. Atmos. Oc. Technol.*
- Numerical simulations of the waves, flows, drifters, and tracer releases during the month of May 2012 have been performed.
- Model-data comparison has taken place
- Manuscript [*Spydell et al.*, 2014] on inlet drifter releases has been submitted to *J. Geophys. Research-Oceans*
- Manuscript [*Feddersen et al.*, 2015] on model data comparison of May 7 dye release is nearly submitted.

RESULTS

1. Aerial dye measurements and maps

Using aerial hyperspectral dye observations that he collected on 4 of the dye releases, combined with in situ jetski based dye observations, we have (a) developed an algorithm for estimating surface dye concentration from hyperspectral observations, (b) found that it works with correlation squared $r^2 = 0.85$ for all 4 dye releases combined, and (c) made aerial maps of surface dye that are very useful in quantifying tracer transport and mixing. This work has been published in *J. Atmospheric and Oceanic Tech.* [*Clark et al.*, 2014]. An example of a sequence of surface dye maps from May 7th is shown in Figure 2.

2. Quantifying Observed Dye Transport and Inlet Exchange

The total amount of dye that is transported out or into the inlet can be estimated from the observations. The total dye transport is defined as

$$T_{\text{dye}}(t) = \int hD\vec{U} \cdot \hat{n}\, dl, \tag{1}$$

where the integral is along the 2–3 m depth contour along the inlet (Figure 1), h is the water depth, D is the 1-min averaged dye concentration, $\vec{U}$ is the 1-minute averaged current vector, and $\hat{n}$ is the outward normal to dl. In these shallow water depths, we assume that the dye is vertically well mixed. The local flux $hD\vec{U}$ is calculated at 9 pressure/velocity/dye observation points spanning the inlet. The integral (1) is calculated via the trapezoid rule across these 9 locations. If a significant amount of dye is transported out of the inlet *between* the sensors then it would imply that the

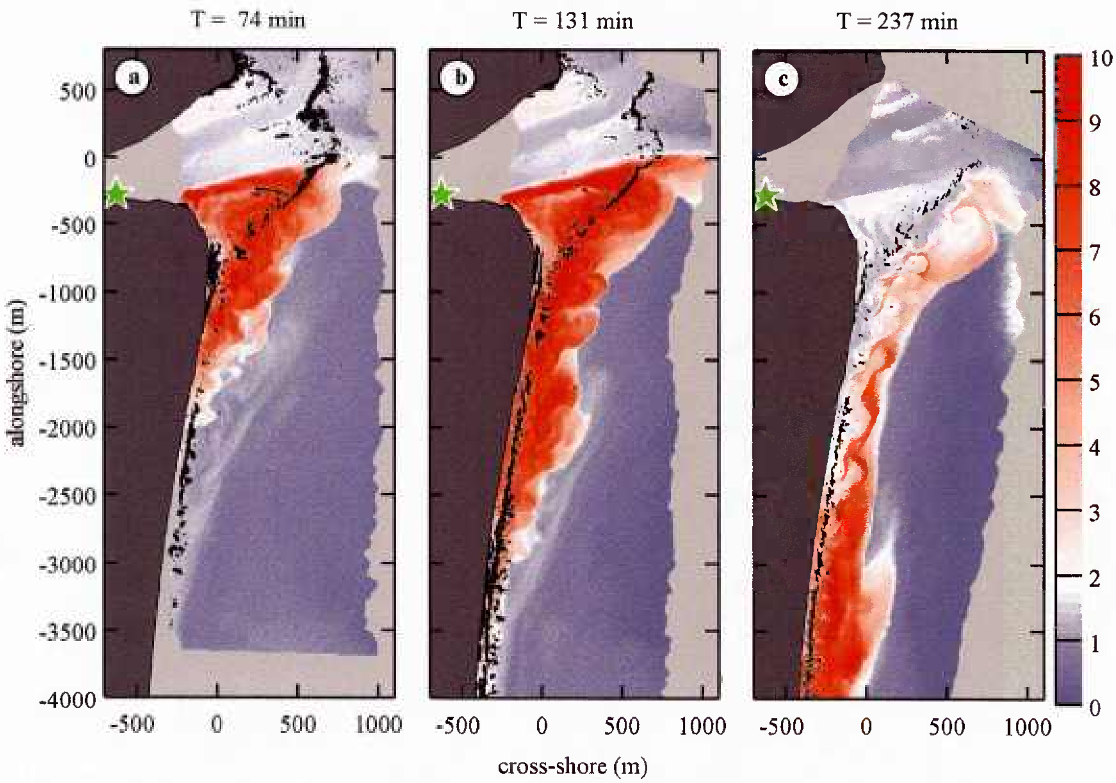

Figure 2: Hyperspectral estimated dye concentrations (ppb, see legend) on 7 May 2012 during RIVET. Dye was released continuously just inside the inlet (green star symbol) from T =0 to 139 min, and image times are noted in the panel titles. Dark gray regions indicate land, light gray regions indicate water outside the imaged area, and black regions indicate foam from breaking waves. From *Clark et al.* [2014].

instrument array did not resolve the dye field. One test for this is if the time-integral of transport T_{dye} equals the total dye released Q_{dye}, or

$$\int T_{\text{dye}}(t)dt = Q_{\text{dye}}? \tag{2}$$

This is examined by use of the statistic δ, where

$$\delta = \frac{\int T_{\text{dye}}(t)dt}{Q_{\text{dye}}}. \tag{3}$$

The dye transport $T_{\text{dye}}(t)$ is estimated for releases R1 (05/06), R2 (05/07), R4 (05/11), R5 (05/12), and R6 (05/19) and is shown in Figure 3. Data coverage on R3 and R7 was poor. On both R1 and R2, δ is near one, indicating that the dye transport out of the inlet was well resolved. On the two point releases R4 and R5, δ is small ≈ 0.2 which indicates that the dye field was

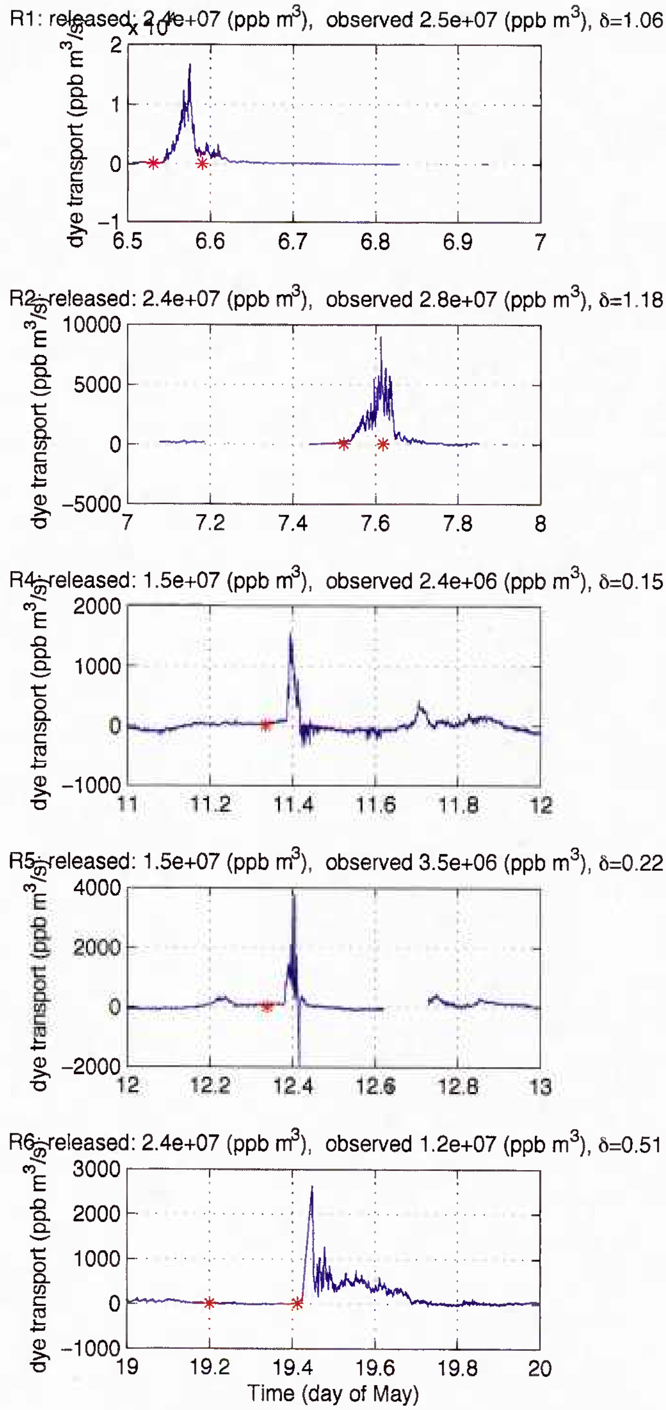

Figure 3: Time series of dye transport $T_{\text{dye}}(t)$ (ppm m^3 s^{-1}) versus time for releases R1 (05/06), R2 (05/07), R4 (05/11), R5 (05/12), and R6 (05/19). In each panel the red asterisks denote the start and end of the dye release. Note R4 and R5 were point releases with one asterisk. Atop each panel is given the total dye released, the total observed dye transported, and δ (3).

not well resolved. Aerial dye images (*e.g.,* Figure 2) on R4 and R5, indicate that the instrument array should have resolved the dye. What happened instead is that the vertical salinity stratification was so strong that the dye stayed in the fresh upper water layer and the dye fluorometers in 3 m water depth did not observed the dye that passed by above them. Release R6 was a 5-hour release spanning flood tide (bottom panel in Figure 3). The dye went up the inlet and the back bay and through the ICW. When ebb tide occured, dye at weak concentrations flowed out the inlet. Over the ebb tide, $\delta \approx 0.5$, indicating that half the released dye that went up the inlet made it back out on the subsequent ebb. This is important in estimating inlet residence times.

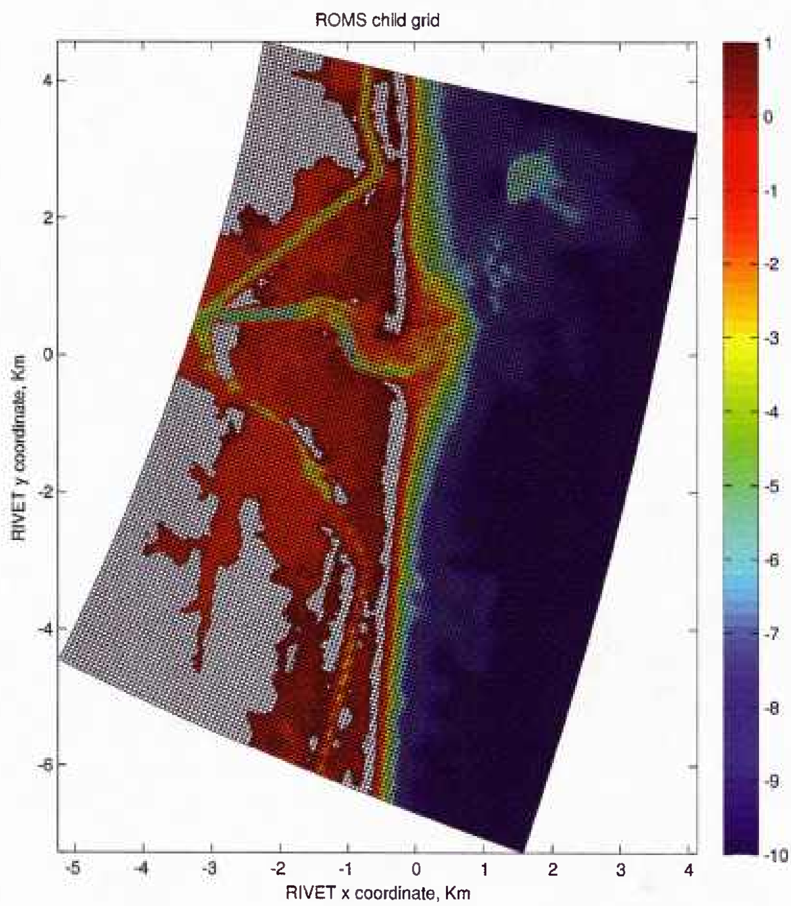

Figure 4: Map of the COAWST (SWAN/ROMS) model grid for the New River Inlet region. Bathymetry is colored (see scale at right) and the land mask is in white. Grid spacing varies between 10–15 m.

3. Tracer Modeling at New River Inlet

In collaboration with Maitane Olabarrieta from the University of Florida, we have performed a number of COAWST (coupled ROMS/SWAN) model simulations of the New River Inlet. This

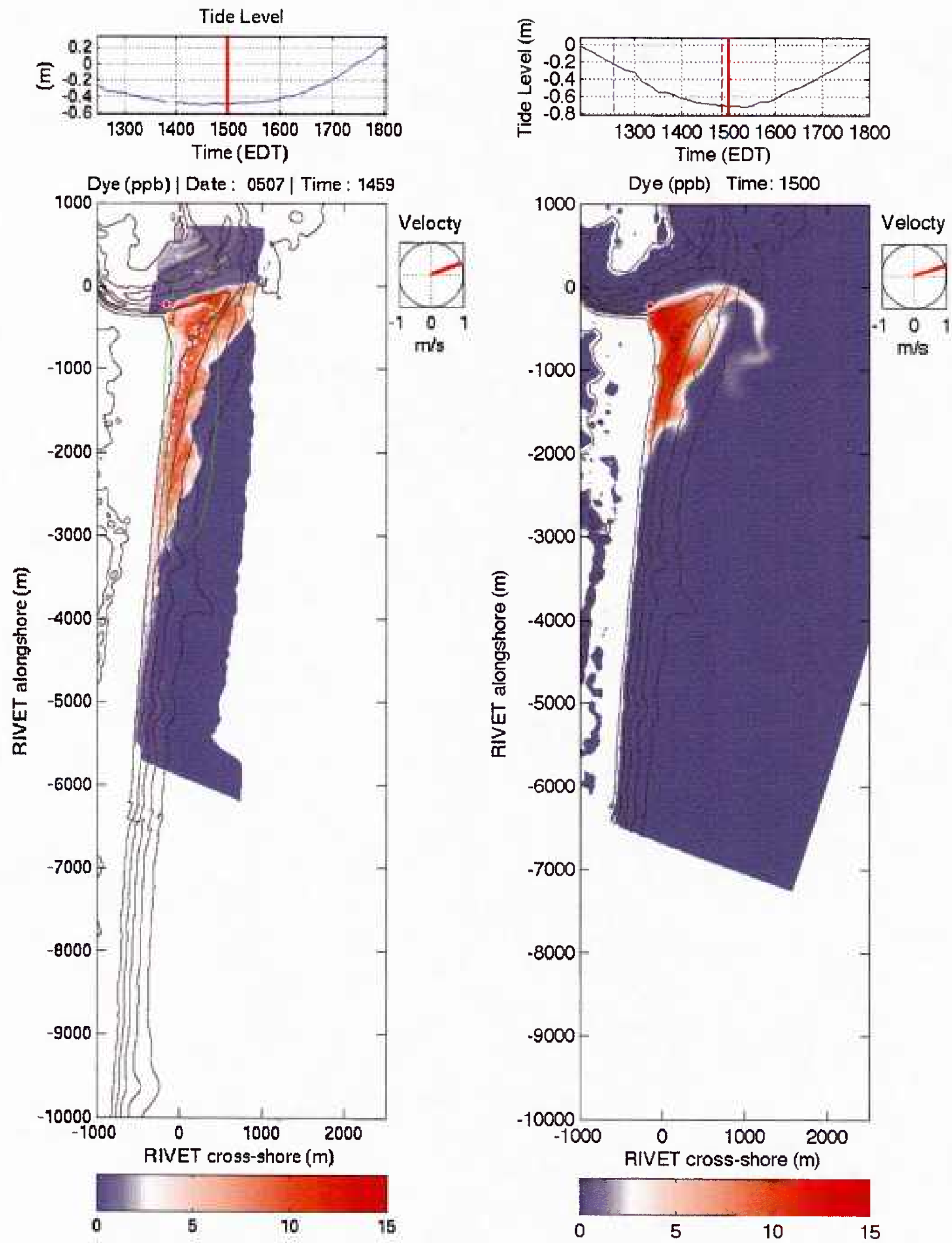

Figure 5: (Left) Observed and (Right) Modeled New River Inlet dye release on May7th at 14:59 EDT. The (top panel) tide is near low. The main panel shows surface dye as a function of x and y in ppb (scale at bottom). The modeled and observed dye field have similar patterns with dye transported over the southern shoal and advecting down coast, although the model down-coast transport is faster than observed. The "velocity" panel just to the right of the dye panel shows the current vector at WHOI ADCP 05 in the heart of the inlet (red dot). Note the similarity of the vector currents. The green ellipse is based on observed dye 2nd moments.

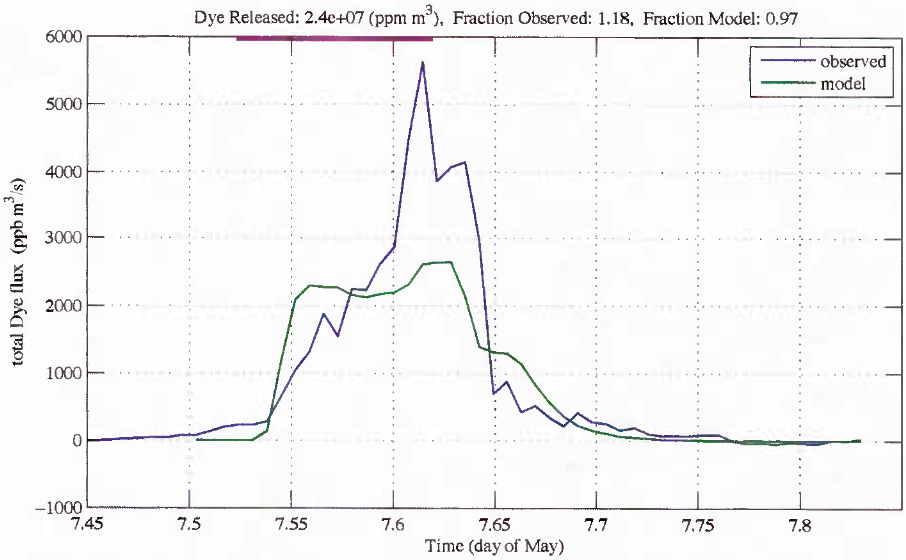

Figure 6: Time series of release R2 dye transport T (ppm m^3 s^{-1}) versus time for observations (blue) and model (green). The time-period of the dye release in the inlet is indicated by the pink bar.

version of the model couples SWAN to ROMS using the vortex-force formalism [*Kumar et al.*, 2012]. A parent grid spanning a 50 km by 30 km is run with ADCIRC tidal forcing, WW3 waves, and observed winds. The simulations on the parent grid are too coarse for detailed simulation of flow and tracer in the inlet. Thus the parent grid simulations serves as boundary condition for simulations on a 7 km by 9 km child grid centered on the inlet (Figure 4), encompassing the ICW and out to 10 m depth in the coastal ocean, and utilizing 15 vertical levels. The model tidal elevations, currents, and waves have been compared to observations at all deployed current meters during the principal 3-week long part of the experiment. As this science topic is reserved for others, particularly Tom Hsu and his graduate student Julie Chen at UDEL, we do not focus on this result.

The dye releases with aerial hyperspectral observations have all been simulated. Here we will focus on the continuous release on May 7th. Many features of the observed May 7th dye release are captured in the model. Model-data comparison movies have been posted on the RIVET-1 blog. A frame of the movie just after the 140 minute dye release ended is shown in Figure 5. The dye pathway over the SW shoal out of the inlet is similar in model and observations.

This similarity can be seen by comparing the time-series of observed and modeled dye transport out of the inlet by integrating the flux over the same boundary (Figure 6). The initiation and duration of the dye transport is similar in both as is the magnitude, but the observed dye transport has a larger maximum - about twice the modeled. This may reflect a limitation in calculating transport from a sparse array. Note that the total observed transport on R2 (May 7th) is 20% larger than the total amount of dye released.

The visual similarity between the modeled and observed dye evolution on May 7th can be further quantified by examining the evolution of the dye center of mass (calculated via 1st moments)

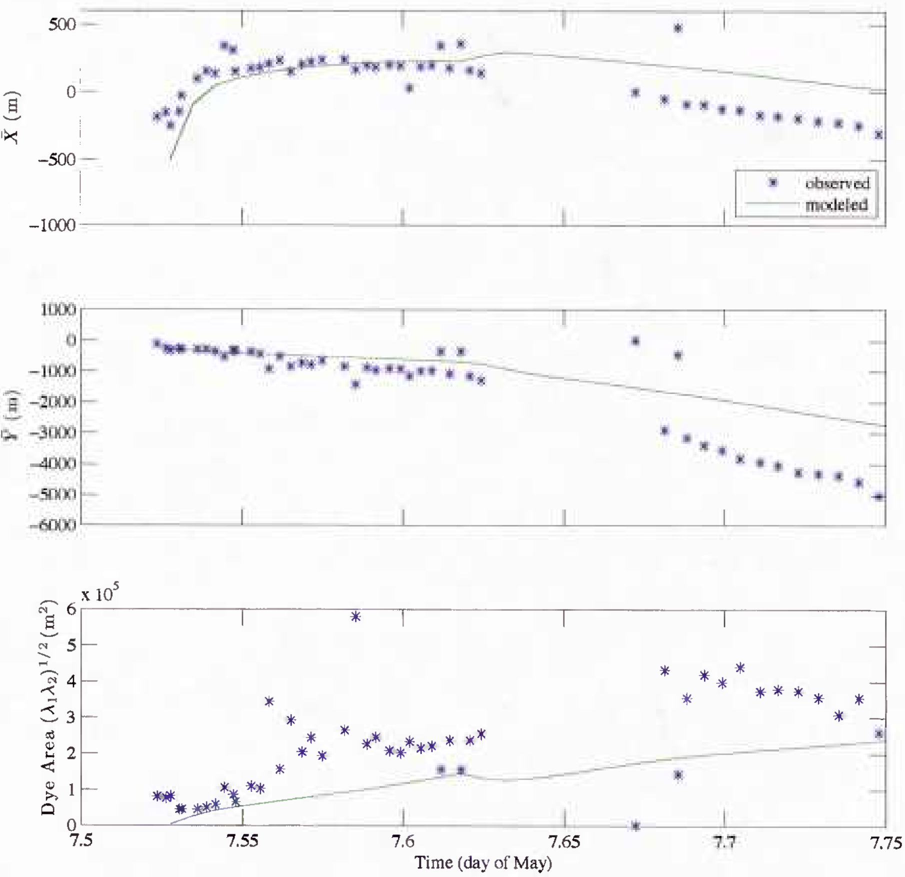

Figure 7: Time series of observed (*) and modeled (solid) May 7th Dye Release moments: (top) Cross-shore dye center of mass $\bar{X}$, (middle) alongshore dye center of mass $\bar{Y}$, and (bottom) dye ellipse area (see Figure 5) derived from 2nd moments.

and dye area (calculated via 2nd moments). The dye center of mass location is very well modeled for $t < 7.65$ day - both in the cross-shore ($\bar{X}$) and alongshore $\bar{Y}$ (top and middle panels in Figure 7). The observed dye area is reasonably modeled - within a factor of 2 (bottom panel Figure 7). he airplane had to return to airport to refuel between $7.63 < t < 7.67$ day.

As can be seen in Figure 6, once dye is past the SW shoal, the observed dye is transported more rapidly down the coast in the "surfzone" than is observed. This can be quantified from the dye moments once the plane resumed sampling. After $t = 7.67$ day, the dye field was advecting down the coast, and the modeled alongshore center of mass $\bar{Y}$ moves down the coast too slowly (see the different slopes in the green curve and the blue asterisks in middle panel Figure 7).

This work is almost submitted to *J. Geophys. Res.* [*Feddersen et al.*, 2015].

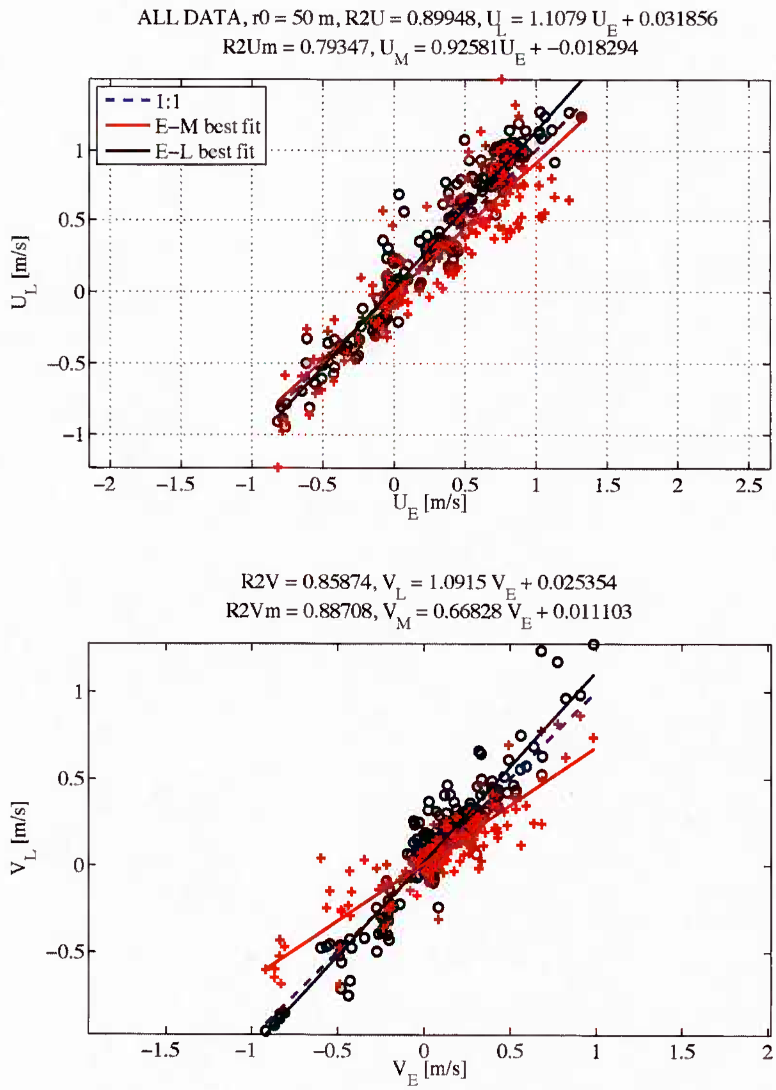

Figure 8: Observed (black) and modeled (red) mean Lagrangian velocities versus Eulerian velocities: (a) RIVET cross-shore, and (b) RIVET alongshore velocities . Best fit and 1-to-1 lines are indicated. On average, observed Lagrangian U and V are 10% larger than current meter values. Cross-shore modeled Lagrangian velocities have more scatter than observed, $r^2_{obs} = 0.9$, $r^2_{mod} = 0.8$. Modeled Lagrangian alongshore velocities are smaller than Eulerian, $V_L \approx 0.66V_E$.

4. Analysis of Drifter Observations and Modeling

Assistant Project Scientist Matt Spydell has been leading the analysis of the RIVET-I drifter observations, and has been strongly collaborating with Tom Hsu and Julie Chen of University

of Delaware and using their SHORECIRC simulations in order to do model-data comparison. To summarize, 35 GPS-tracked drifters were deployed on 8 days of May. An average of approximately 140 drifter hours of data was collected per day. Specifics on the drifter release experiments and visualizations can be found on the blog here. The analysis has been written up and submitted for publication in the *Journal of Geophysical Research* [*Spydell et al.*, 2014].

Here, two aspects of the drifter analyses are briefly summarized. First, we compare observed and modeled Lagrangian velocities to the observed (both our own and Raubenheimer/Elgar) ADCP (depth-integrated) and ADV measurements. Lagrangian velocities are binned when they are within 50 m of a current meter and then averaged over a single drifter release. As the Eulerian velocity observations are considered closest to the truth, this allows us to both test the water following properties of the SIO drifters and the accuracy of the model. Some difference is expected because the drifters sample near the surface and many of the current meters sample near the bed.

The primary result is that the observed Lagrangian drifter velocities are quite similar to the Eulerian observed velocities (black symbols in Figure 8, confirming that the drifters are water following. The second is that the modeled Lagrangian velocities are correlated with but too weak (by 1/3) relative to the Eulerian observations (red symbols in Figure 8).

Such differences in observed and modeled Lagrangian velocities will lead to very different drifter trajectories. This is illustrated in Figure 9 where the observed (black) and SHORECIRC modeled (red) drifter trajectories are quite different. Although there was little wind this day, the observed trajectories take a left turn coming out of the inlet whereas the model drifters simply head out the main channel. Drifter dispersion statistics (not shown) are also quite different between the model and observed. How to resolve this (*i.e.,* what is missing in the model) is currently being investigated.

IMPACT/APPLICATIONS

This work will have significant impacts for Science and/or Systems Applications because it will provide (a) understanding regarding the current state of the art model deficiencies in terms of correctly modeling transport and dispersion, (b) guidance in how to improve these models, and (c) provide a testbed for future models.

RELATED PROJECTS

This project is part of the Tidal Inlets and River Mouths DRI. The field work was part of the RIVET-I field experiment held at the New River Inlet in NC. This effort is collaborative with many other RIVET-I experiment participants (Raubenheimer/Elgar/MacMahan/LIppmann/Terrill/Hsu). In addition, through this work we have developed a strong collaboration with Prof. Maitane Olabarrieta from the University of Florida who has performed all of the COAWST model simulations.

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Clark, D. B., L. Lenain, F. Feddersen, E. Boss, and R. T. Guza, Aerial imaging of fluorescent dye in the nearshore, *J. Atmos. and Ocean. Tech., 31*, 1410–1421, doi:10.1175/JTECH-D-13-00230.1, 2014.

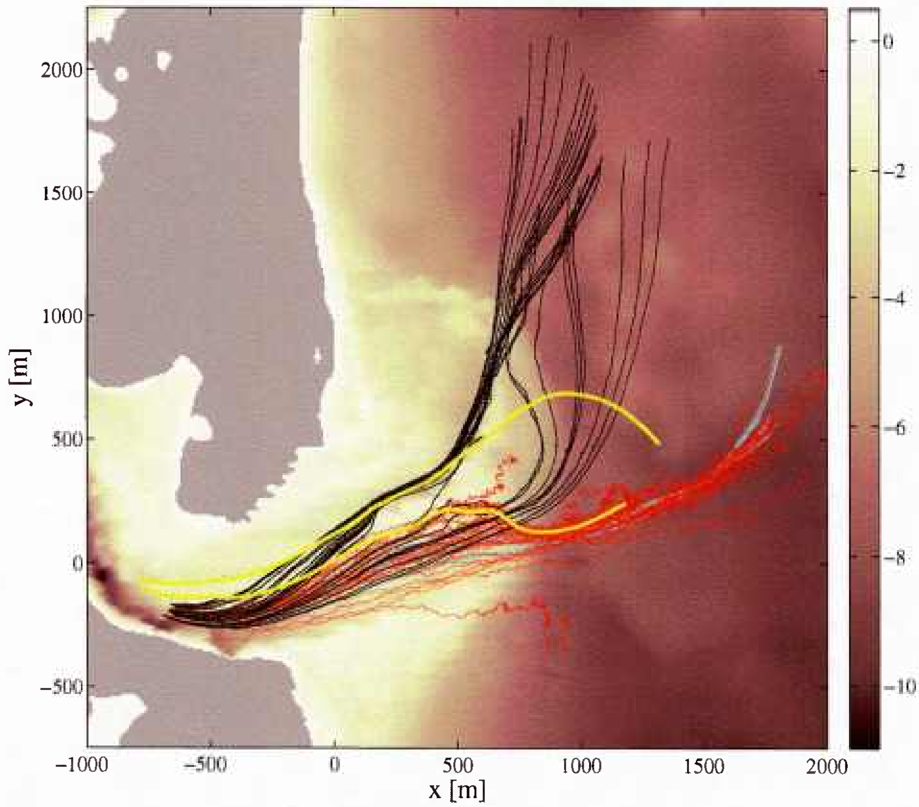

Figure 9: Observed drifter tracks (black) for one ebb tide release. Modeled drifter tracks with (red) and without (cyan) small scale ($K = 1\ \mathrm{m}^2\,\mathrm{s}^{-1}$) diffusivity are released from the same location and time as observed tracks. Modeled tracks released slightly further up the inlet are indicated in yellow. Notice the distinct difference in exit paths and final locations of observed and modeled drifters. Modeled dynamics include tide, wind, and wave forcing.

Feddersen, F., M. Olabarrieta, R. T. Guza, D. Winters, B. Raubenheimer, and S. Elgar, Observations and modeling of a tidal inlet dye tracer plume, *J. Geophys. Res.*, in prep, 2015.

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PUBLICATIONS,

Publication from this project include

- Clark, D. B., L. Lenain, F. Feddersen, E. Boss, and R. T. Guza, Aerial imaging of fluorescent dye in the nearshore, *J. Atmos. and Ocean. Tech.*, 31, doi:10.1175/JTECH-D-13-00230.1, 1410-1421, 2014.
- Spydell, M. S., F. Feddersen, M. Olabarrieta, J. Chen, R. T. Guza, B. Raubenheimer, and S. Elgar, Observed and Modeled Drifters at a Tidal Inlet, submitted to *J. Geophys. Res.*, 2014.
- Feddersen, F., M. Olabarrieta, R. T. Guza, D. Winters, B. Raubenheimer, and S. Elgar, Observations and Modeling of a Tidal Inlet Dye Tracer Plume, in preparation for *J. Geophys. Res.*, 2015.